Tomographic Scanning Imaging Seeker

Harald Hovland
Norwegian Defence Research Establishment
Postboks 25, NO-2027 Kjeller
NORWAY

harald.hovland@ffi.no

ABSTRACT

The tomographic scanning (TOSCA) imaging seeker concept is presented. The system is based on conical scan reticle seeker optics modified with an eccentrically rotating circular aperture. After signal pre-processing, an image is extracted using tomography reconstruction techniques. Simulation results are provided to show the reconstruction quality. The concept, using a single pixel and a simple rotating axis scan mechanism, allows for a simple, low-cost, software-driven imaging sensor. Imaging capabilities against air targets are discussed.

1.0 INTRODUCTION

1.1 Historical Development

The discovery of infrared (IR) radiation was done more than two centuries ago by Herschel [1], and the use of this radiation in military applications was proposed almost a century ago by Lindemann [2]. Technical difficulties, notably in material sciences, prevented its use during World War II despite both Allied and German efforts [2,3], and it was not until 1953 that the first successful test of an IR seeker was made with the AIM-9 "Sidewinder" missile [4]. Simplicity was a success factor in missile design for several decades, but more complex and hostile scenarios as well as efficiency requirements have pushed the requirements for seeker performance to a point where imaging of the scene has been found advantageous, and several missile systems are now being fielded with imaging sensors, notably the new AIM-9X Sidewinder, IRIS-T, ASRAAM and Python-5. The highly sophisticated seekers in these missiles contribute to a significant portion of the total system cost, and the TOSCA concept is looked upon as a low-cost alternative to traditional imaging sensors. Although the TOSCA principle is an imaging concept based on a (non-imaging) seeker design, it is not limited to missile seeker applications.
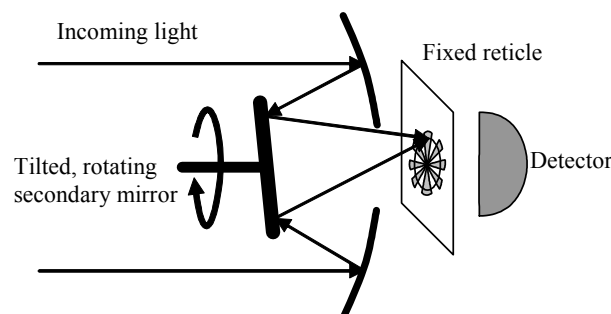

Figure 1: Principle of the conical scan reticle FM seeker.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 OCT 2005	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Tomographic Scanning Imaging Seeker	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Norwegian Defence Research Establishment Postboks 25, NO-2027 Kjeller NORWAY	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM202114, RTO-MP-SET-094. Emerging EO Phenomenology (Naissance de la phenomenologie et de la technologie electro-optique)., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

1.2 The Con-scan Reticle Seeker

The TOSCA seeker concept is based on the con scan reticle seeker. A sketch of the basic conical scan FM seeker optics is shown in figure 1. Focussing optics projects a target image onto a fixed reticle consisting of transparent and non-transparent sectors. The optics have an off-axis tilt and are rotating, scanning the image in a circular movement onto the reticle. A detector is placed behind the reticle, and detects light passing through the transparent fields of the reticle. The transparent fields of the reticle are traditionally distributed evenly around a central point, as seen in figure 2.
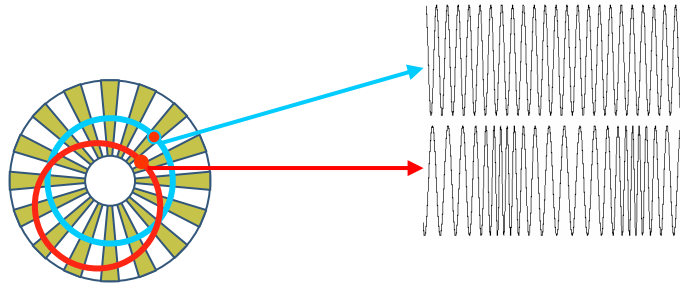

Figure 2: Typical conical scan FM reticle and two signals produced by it.

The nutating optics scans the target image in a circular fashion in such a way that a centred target image follows a circular trajectory around this central point. Assuming the target image is a slightly blurred spot, a centred target will produce a sinusoidal signal with constant carrier frequency. If a target is slightly off-axis, the circular image scan trajectory will be moved sideways. The width of the fields crossed by this circle closer to the reticle centre will be smaller, leading to a higher signal frequency in that region than at the opposite side, where the distance to the reticle centre is bigger, and hence the fields are wider. This leads to a frequency modulation of the carrier signal. The phase and amplitude of the frequency modulation can be extracted to determine the hot spot position.

The concept of hot spot tracking was found suitable in air target scenarios, as the background in short- and mid-wave IR is relatively homogeneous in comparison with the typically high contrast aircraft targets. In more complex environments, such as cluttered background and/or when countermeasures are present, simple hot spot tracking may not give a satisfactory performance. Several proposals have been made to counter these issues. In addition to pure counter-countermeasures techniques, proposals have been made for multi-pixel reticle sensors [5,6], and a combination of a two-colour reticle seeker using sophisticated statistical methods known as independent component analysis [7,8]. The first proposal involves a fairly complex setup, and the second method is only capable of resolving a very limited number of point sources.

2.0 THE TOSCA CONCEPT

One fundamental property of the con-scan system is that the image projected onto the reticle in a con-scan system maintains its orientation at all times. The target image movement is thus translational. The reticle, with its transparent and non-transparent fields can be considered as a superposition of several knife-edges across which the target image is scanned, as shown in figure 3. We will now examine what happens when the target is scanned across such a knife-edge.

Assuming the target signature changes are negligible during a scan, the time derivative of the signal is only due to the amount of the target image that crosses the knife-edge per unit time. This amounts to a line integral along the knife-edge at any given time. This means that the time derivative of the signal is proportional to a line-scan of the target. Using the so-called Fourier slice theorem [9], the Fourier transform of the derivative signal are found to lie on a line in the Fourier space of the image plane. The orientation of these lines is identical to the knife edge normal.

This was the first key point in the development of the TOSCA concept. The second key point was the fact that the target orientation remains constant, whereas the knife-edges appear at regularly distributed angular orientations. It is thus possible to fill the Fourier plane with points lying on lines around the origin with evenly distributed orientations. The discovery of these elements lead to the development of the TOSCA principle in 2004 [10].

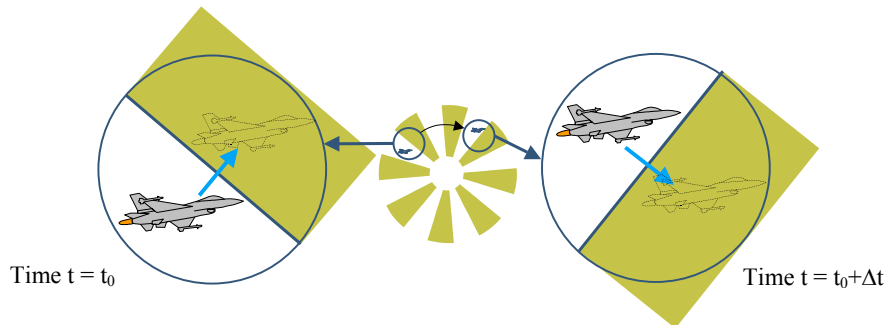Time t = t_0 Time t = $t_0 + \Delta t$

Figure 3: Details in the conical scan process: The image retains its orientation at all times, whereas the knife-edges scan the target at well defined, evenly distributed angles.

2.1 The Specialized TOSCA Seeker

One problem with the basic system was that the image was the superposition of several knife-edges, all seeing the scene and giving contributions at the same time. This produces aliasing artefacts. Another problem is the limited extent of the knife-edges, which produces effects that are difficult to handle. The reason is that a bright source may exist in the outskirt of the scene, and produce significant line artefacts that are difficult to predict. The solution to these two issues lay the foundation of the specialized TOSCA [11]. The hardware in the specialized TOSCA differs from the general one in that a circular aperture, rotating together with the focussing optics, the centre of the circle being located at the focal point of a centred incoming beam. Ideally, this will reduce the effective field of view in such a way that it stays time invariant (assuming the sensor orientation is fixed). The aperture diameter should be set such that only one knife-edge is overlapping the aperture at any time. The resulting configuration is shown in figure 4.

Fixed reticle

Detector

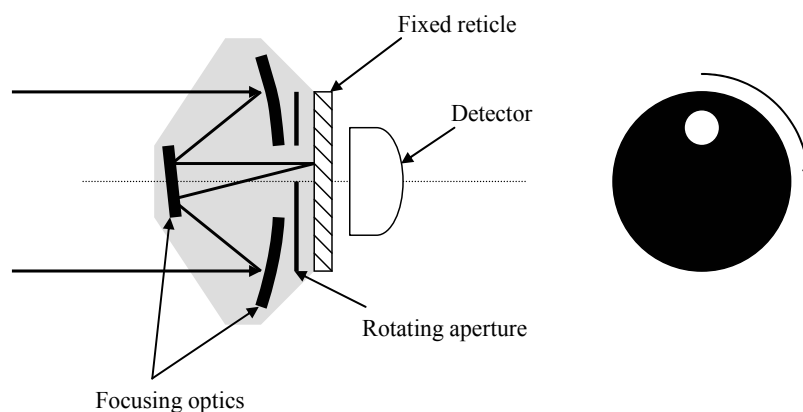Rotating aperture

Focusing optics

Figure 4: Schematic setup of the specialized TOSCA configuration (left), differing from the general by the insertion of a rotating circular aperture (right).

The effect of this aperture is that the signal can be considered piecewise as a knife-edge scan with a single, infinitely long knife-edge, facilitating the mathematical processing. The reason is that the aperture will

pose the limits to the field of view, not the length of the knife-edge. The use of the rotating aperture enabled the reconstruction of much more complicated scenes. It could be added, though, that in the case of a very homogeneous background compared to the target contrast, the aperture is not necessary.

The filtered back-projection is a technique that is popular in computer tomography (CT) reconstruction. It was invented by Bracewell and Riddle in 1967 [12], and is based on the fact that the lines obtained in Fourier space does not give full coverage. Instead, the point density that is approximately inversely proportional to the distance from the origin is compensated for by multiplying the components obtained in Fourier space by a factor proportional to its distance from the origin. This is illustrated in figure 5. It is now possible to take the inverse Fourier transform of the filtered Fourier components and obtain a reconstruction of the image through back projection.
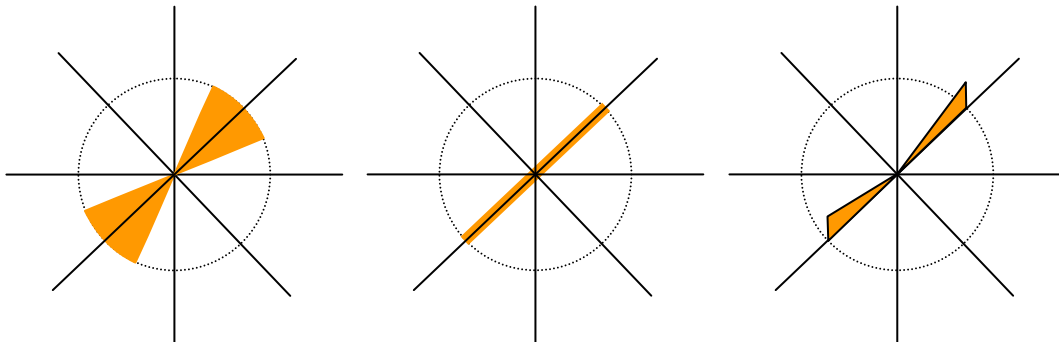

Figure 5: Filtered back-projection approximation used in the TOSCA reconstruction: Instead of sampling a sector in Fourier space (left), only a line is sampled (middle). This is compensated for by weighting the components by their distance from the Fourier space origin (right).

2.2   Image Quality and Specific Air Target Issues

The spatial resolution of a system is generally limited by the number of samples taken as well as the system dynamics and noise figures. In the TOSCA imaging system, there will also be a compromise between the number of scan angles and the number of samples made for each knife-edge scan. For a general purpose image, where image features of interest can be assumed to be evenly distributed and of any size, it would be reasonable to assume that the points in Fourier space should be evenly distributed. This would lead to a requirement of a high number of knife-edge scans compared to the number of samples per knife-edge scans. This may be different in air target tracking scenarios, where a small number of point targets should be positioned with high accuracy, a requirement that would favour a higher amount of samples per knife-edge scan.

A second requirement that may counter this is the requirement for the reduction of false targets. In the extreme case of only two knife-edge scans, where the knife-edges are orthogonal to each other, two targets of equal size will produce four lines having four intersections. These four intersections would have equal intensities and would appear as four identical targets, of which two would be non-existing. The increase in the number of scan directions would increase the number of potential virtual (non-existing) targets, but would reduce their intensity compared to the real targets.

3.0   SIMULATIONS

Several images have been reconstructed to show the performance achieved using the TOSCA imaging technique. The first image obtained using the general TOSCA system (not including the moving circular aperture) is shown in figure 6 together with the original (synthetic) image and the reticle used. The image

is reconstructed using unfiltered back-projection, and the image appears smeared due to the high amount of low-frequency components. It is nevertheless possible to identify the two sources with their correct positions, of which one (the aircraft) is shown to be extended. A close-up of the original and reconstructed images can be seen in figure 7.
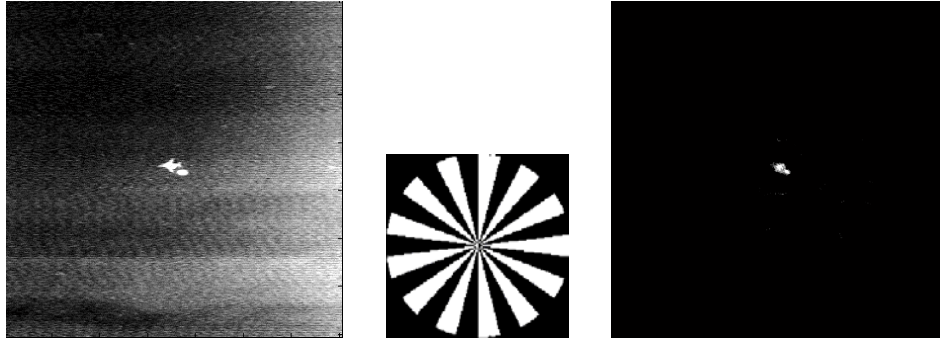

Figure 6: Original image (left), the reticle used to scan it (middle) and the reconstructed image, using the general TOSCA setup and an unfiltered back-projection reconstruction algorithm.
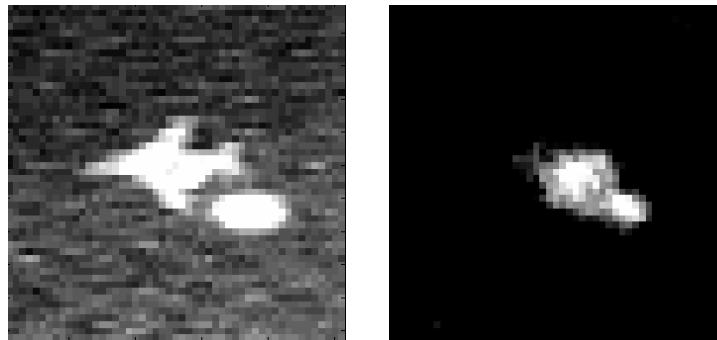

Figure 7: Close-ups of the images in figure 6.

Figure 8 shows the limitation of the general TOSCA system, where several objects produce severe artefacts due to aliasing and rim effects. The imaging potential is demonstrated, though. In the central portion close-up in figure 9, a small virtual object appears in the lower right corner.
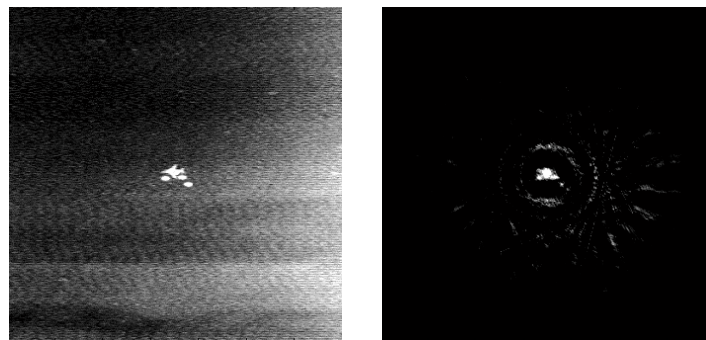

Figure 8: Image showing the limitations of the general TOSCA setup, mainly due to aliasing.
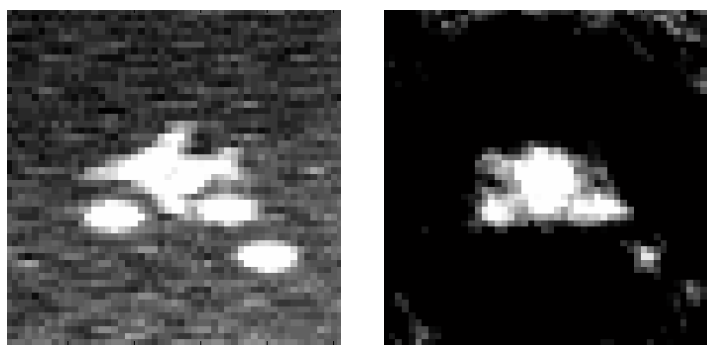
Figure 9: Close-up of figure 8. Note the faint virtual object in the lower right corner.

The improvement of the performance due to the introduction of the moving aperture is shown in figure 10. It should be said that the reticle size in now not the same, but the field of view is maintained. The improvements consist mainly of removing the artefacts. The image is still smeared out due to the unfiltered back-projection technique used.
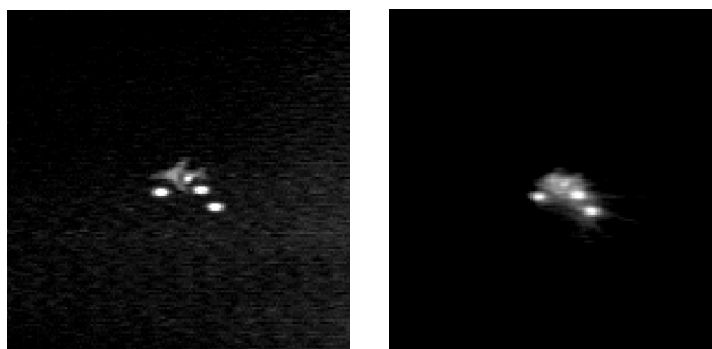

Figure 10: Image showing the improvements of the specialized TOSCA setup with the original (left) and the reconstructed image (right), compared with the general TOSCA shown in figure 9. The image is still somewhat smeared out due to the unfiltered back-projection.

Figure 11 shows the effect of using the filtered rather than the unfiltered back-projection algorithm.
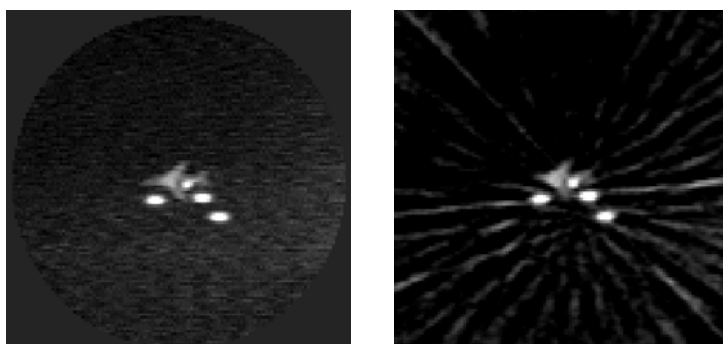

Figure 11: The use of the filtered back-projection algorithm on the signal obtained with the specialized TOSCA-configuration gives a crisper image, showing more details of the aircraft. It also highlights some hot spot artefacts due to the relatively low number of knife-edges.

It is now possible to see the details of the aircraft fairly well, especially taking into account that most of the information in the signal is contained in a 40x30 pixel rectangle and the main information in the knife-

edge-scan signal is contained in approximately 40x13 sample points (the factor 13 appears due to the number of independent knife-edge orientations). It is also possible to see the hot spot "ripple" artefacts due to a low number of knife-edge scans.

It is of course possible to increase the number of knife-edges, typically up to 50-100 knife-edges, although this requires more processing power. Figure 12 shows the reconstruction obtained with 60 independent knife-edges. The ripples have now vanished.
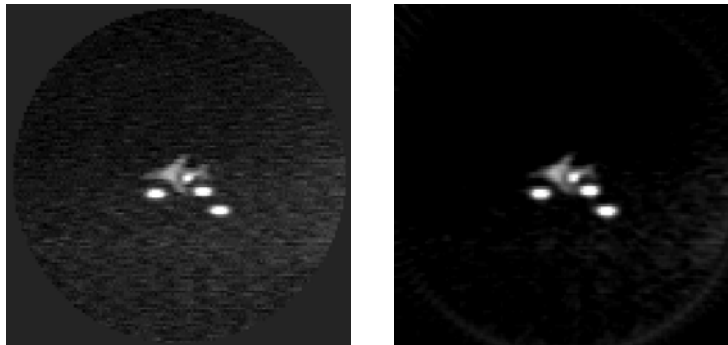

Figure 12: The reconstruction here is similar to that of figure 11, but with 60 independent knife-edge angles (the number is equal to the aperture radius). More details of the aircraft are visible, and the "ripple" artefacts have now disappeared.

Finally, figure 13 is used to show the imaging properties of the system for more general purpose imaging. The original image is 440x440 pixels; whereas the 60 scan lines has 440 samples each. The image information stored thus represents approximately 1/7 of that of the original, prior to any compression. The application of 220 lines would essentially have reproduced the original image without any significant distortion.

Figure 13: The original (left) and reconstruction (right) of "Lena". The original is 440x440 pixels, the aperture used has a 220 pixel radius, and 60 independent knife-edge angles are used.

4.0 SUMMARY

A presentation of the background of the TOSCA imaging technique has been presented, including an overview of the hardware required to realize it. The main reasons for going to the specialized version of this imaging technique have been presented, and its superior imaging qualities have been demonstrated through simulations. Some aspects of the TOSCA performance parameters with respect to air target applications have been discussed. Finally, images obtained from simulations of various refinements of the

system are presented to show the progress achieved. Through detailed simulations, the TOSCA imager is found to be working as a principle.

5.0   REFERENCES

[1]   W. Herschel, "Experiments on the Refrangibility of the invisible Rays of the Sun", Phil. Trans. Pt. II, 90, 284-292 (1800).

[2]   R. V. Jones, "Infrared detection in British air defence, 1935-1938", Infrared Phys., 1, 153-162 (1961).

[3]   E. W. Kutzscher, Proc. IRIS, 1, 5 (1956).

[4]   Federation of American Scientists web page, http://www.fas.org.

[5]   R. G. Driggers, C. E. Halford, G. D. Boreman, "Marriage of frequency modulation reticles to focal plane arrays", Opt. Eng., 30, 10 (1991) 1516-1521.

[6]   H. K. Hong, S. H. Han, J. S. Choi, "An improved reticle seeker using the segmented focal plane array", Proc. SPIE 2744 (Apr. 1996).

[7]   I. Kopriva, H. Szu, A Peršin, "Optical reticle trackers with the multi-source discrimination capability by using independent component analysis", Opt. Comm. 203 (2002) 197-211.

[8]   H. Szu, I. Kopriva, A Peršin, "Independent component analysis approach to resolve the multi-source limitation of the nutating rising-sun reticle based optical trackers", Opt. Comm. 176 (2000) 77-89.

[9]   A. C. Kak, M. Slaney, Principles of Computerized Tomographic Imaging, IEEE Press (1988) 56-57.

[10]   H. Hovland, "Tomographic scanning imaging seeker", Proc. SPIE 5430, 76-85 (2004).

[11]   H. Hovland, "Specialized tomographic scanning imaging seeker", Proc. SPIE 5778, 725-731 (2005).

[12]   R.H. Bracewell and A.C. Riddle, "Inversion of fan beam scans in radio astronomy," Astrophysics Journal, vol. 150, pp. 427 - 434, 1967.